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Investigation on cypress wood membrane for water filtration

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An efficient yet inexpensive, biodegradable, and readily available filtration system is needed for countering the threats of unsafe water. This research aims at studying gymnosperm xylem tissue as a potential alternative to the polymeric membranes that involve a huge cost and energy for their manufacturing and are also not environmentally friendly. The xylem conductive tissue of tree trunk was investigated in the present study to act as a membrane for water filtration. This is attributed to the presence of pores in pit membranes which makes them permeable to liquids. The size of these pores fits well for the application of microfiltration. Kashmiri Cypress (*Cupressus cashmeriana*) was used in this study. A pressure-driven filtration process was used to determine the efficacy of the filter. Particle size analysis was done on the filtrate. The results demonstrated the feasibility of the setup for use in domestic applications. A gymnosperm xylem filter used in this study was able to effectively filter out particles > 300 nm. A flow rate of 4 liters per day was obtained under a pressure of 0.295 bar, with filter diameter of 1cm and 0.75mm thickness. Fourier Transform Infrared Spectroscopy test was conducted on the filtrate to determine the constituents of the filtrate. The test revealed that the chemical composition remained unchanged after filtration.

Keywords: Xylem filtration; Pit membranes; Microfiltration; Particle size analysis; FTIR

INTRODUCTION

The dearth of safe and clean drinking water is a major reason of mortality in the underdeveloped countries. Potable or drinking water is one having acceptable quality with respect to physical, chemical, and bacteriological parameters so that it can safely be used for drinking and cooking purposes [1]. The most deadly water pollutants are of biological origin. The most recurrent and global health hazards associated with drinking water are infectious diseases caused by pathogens such as bacteria, viruses, protozoa, or parasites [1,2]. Among these, widespread waterborne pathogens are bacteria (e.g. *Escherichia coli*, *Salmonella typhi*, *Vibrio cholerae*), viruses (e.g. adenoviruses, enteroviruses, hepatitis, rotavirus*)*, and protozoa *(*e.g. *giardia)* [1].These pathogens lead to child mortality and also give rise to malnutrition and retarded growth of infants. The WHO has reported that around 1.6 million humans lose their life every year due to the diarrheal diseases attributed to non-availability of safe drinking water and proper sanitation [3]. The children under the age of 5 years constitute 90% of these mortalities, mostly prevalent in developing countries. Therefore, to prevent the spread of waterborne diseases multiple barriers including prevention of contamination, sanitation, and disinfection are necessary [1]. However, if only one barrier is possible, it has to be disinfection unless evidence exists that chemical contaminants are more harmful than the risk from ingestion of microbial pathogens [1]. Additionally, water quality control at the place of use is most effective due to the issues of regrowth of microbes, by-products of disinfectants, corrosion of pipelines and contamination in the distribution system [2,4]. Chlorination, filtration, UV-disinfection, pasteurization/boiling, and ozone treatment are some common techniques for water disinfection [1,2,5]. Though at large scale chlorine treatment is effective, it is expensive for smaller places like towns and villages. Also, boiling is an effective method for water disinfection; but the cost of fuel required to disinfect water is expensive [1]. Disinfection with UV radiation is a promising point-of-use technology available today [1], Again it requires electricity and maintenance of a UV lamp, or enough sunlight. Under these circumstances small and cheap filtration equipment can satisfactorily solve the problem of point-of-use disinfection. Unfortunately, there does not exist an ideal technology for this purpose. The carbon-based filters are inexpensive, but are not effective in expunging pathogens [1]. Sand filters offer an excellent substitute that can remove pathogens but they require a sizeable area and maintenance knowledge [1]. The membrane filtration processes capable of removing pathogens [2,4] have high cost, undergo membrane fouling, and require power for pumping water on account of low flow rates [6], hence, are difficult to have their wide implementation in developing countries.

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In this regard, novel processes are urgently needed which outperform current technologies. To be precise, membrane materials that are cheap, readily available, effective at pathogen removal and finally disposable, could considerably impact our capability to provide clean drinking water. A hope for this purpose comes from the nature itself. A potential solution exists in the form of plant xylem which is a porous material that conducts fluid in plants [7]. Plants have specialized xylem tissues to transport sap from their roots to the shoots. Xylem tissues have developed under competing pressures, offering minimal resistance to the ascent of sap while maintaining the structure of small nanoscale pores to prevent cavitation. The size of these pores typically varies from few nanometers to around 500 nm, depending on the species of plants [8]. The plant xylem happens to be an ideal material for filtering out pathogens. This presents an opportunity to researchers to investigate whether plant xylem can be adopted as an inexpensive water filtration device.

The xylem tissue has tiny ducts working in parallel (Fig. 1(a)). The elements of conduction in xylem tissue vary in angiosperms and gymnosperms (Fig 1(b)). In gymnosperms, these ducts are present as unicellular dead elements called tracheids. Tracheids can have a diameter and length up to 80 mm and 10 mm, respectively. Vessels are the elements of water conduction in angiosperms. The vessels may have a diameter up to 0.5 mm, while their length ranges from a few millimeters to a few meters [9]. Pits connect these conducting elements with their adjacent ones. The pit membranes have pore size ranging from a few nanometers to a maximum of around 500 nm, depending on the plant species. Pores in the pit membranes werethe basic filtration unit in this research. The angiosperms have longer vessels and, therefore, to force water through the pit membrane, a large thickness of the xylem is required. In angiosperms, xylem tissue makes up a smaller fraction of the cross-sectional area of the trunks and branches and hence was not used. The shorter tracheids in the xylem tissue of gymnosperms are ideal for the purpose. Correa and Sens [10] investigated the pine, virola, and cedar wood membrane for filtration. The study investigated the removal of color and turbidity with the flow in the perpendicular direction of fibers. There was a small difference in respect to the efficiency of membranes with a thickness between 1.0 and 2.0 cm. The membranes were in the range of 30–35% efficiency for color and turbidity. The membrane with a thickness of 3.0 cm had enhanced performance with 50% average efficiency for color and turbidity. It has been found that the anisotropy of wood poses challenges when deformation occurs with loss or gain of humidity leading to cracks during the drying process. The use of wood membrane filters intended for the separation proved to be effective. Several processes are in the initial phase of development, in which the main determining factor is the relationship between filtration and the pore size of the filtered material. Due to the geometric conformation of membranes, the filtration performed in a conventional manner passes in the cross-flow direction. The reason being that the flow observed certain turbulence on its surface which results in the dragging of particles that cause incrustation. With cross-flow filtration, it is advisable to apply some pressure to "push" fluid through the pores of the membrane for collection on the other side. The applied pressure must comply with the manufacturer's recommendations to avoid surface damage. The wood is mainly composed of lignin (ranging from 18 to 35%), hemicelluloses, and cellulose (ranging from 65 to 75%) polymeric materials which are considered complex, particularly polymeric substances. A study of filter elements with varying degrees of thickness to establish a relationship between wall thickness and efficiency was performed by Correa and Sens [10]. In order to understand the water transport through wood, familiarity with its chemical composition is important. These compositions vary according to several factors, such as geographic location, climate, and soil type. Therefore, the chemical composition is not accurately defined for a wood species or even for a specific wood. There are other components that are present mainly in the form of extractable organic and inorganic substances, such as oils, resins, sugars, starches, tannins, nitrogenous substances, organic acids, and organic salts (ranging from 4–10%). These extracts contribute to the organoleptic properties of wood, such as smell, color, taste, and its resistance to fungi and insects. The elements that make up the wood, in general, are carbon (50%), oxygen (44%), hydrogen (5.5%), and traces of many metal ions [2]. Sens *et al.* [11] studied dead-end filtration and helical cross-flow in wood. The three species of wood studied were: caixeta (*Tabebuia cassinoides*), garapuvu (*Schizolobium parahyba*), and pine (*Pinus elliottii*). They concluded that the filtration obtained was microfiltration, and filtration in the perpendicular direction was found to be infeasible. Boutilier *et al.* [12] conducted experiments on wood from white pine (*pinus strobus*). They used deionized water for the experiments. Red pigment (Higgins Ink), 20 nm fluorescent polystyrene nano-spheres, and inactivated fluorescent dye-labeled *Escherichia coli* were also used.

Studies revealed that the sap flow rate in plants in the range of several liters per hour may be feasible with less than 10 cm-sized filters, using only hydrostatic pressure to drive the flow [7]. The investigation first of its kind on the pine, *pinus strobus,* which grows in USA was used by Boutilier *et al.* [12]. Nile-red coated 20-nm fluorescent polystyrene nano-spheres and Alexa 488 fluorescent dye-labeled *Escherichia coli* were used in this study. The present study aims to investigate the filtration characteristics of the *Cupressus cashmeriana* so as to find if it can be used as a filtration material. Since the safety of drinking water is a critical issue in this part of the world the Kashmiri cypress was chosen because of its availability.

In this context, new approaches that can improve upon current technologies on the grounds of expenditure, biodegradability, availability are urgently needed. A potential solution exists in the form of plant xylem – a porous material that conducts fluid in plants. Plants have evolved specialized xylem tissues to conduct sap from their roots to their shoots through the process of transpiration. Under competing pressures, the xylem has evolved into a robust conductive tissue that efficiently allows the flow of sap while also preventing the cavitation and development of bubbles that could halt the process.

Various experiments were performed on this tissue to reveal about its permeability and various factors affecting it, necessary for development of a cost-efficient filtration system to serve the purpose.

In angiosperms, xylem tissue constitutes a smaller fraction of the cross-sectional area of the trunks and branches and hence was not used. The observed conductivities were in the range of $5\text{-}6\times10^{-10} m^2Pa^{-1}s^{-1}$. Their pigment filtration experiments revealed a size cutoff of about 100 nm and most of the filtration occurred within the first 2-3 mm of the xylem filter. The xylem filter had a bacterial rejection rate exceeding 99.9%. Ericson *et al.* [6] conducted permeability experiments on wood and analyzed the factors affecting the rate of flow. The fluids used were zinc chloride, water, and benzene.

The present study aimed to investigate the filtration capability of Kashmiri cypress scientifically known as *Cupressus cashmeriana.* The experiments were performed to study the permeability and filtration capability necessary for developing a cost-efficient filtration system to serve the purpose. Post the experimentation, particle size analysis (PSA) was performed for determining the size range of the particles in the unfiltered and filtered samples.

To evaluate the chemical composition of both the filtered and unfiltered samples, Fourier Transform Infrared Spectroscopy (FTIR) was used.

EXPERIMENTAL SETUP

Materials and methods

The setup comprised an air compressor (Fig. 2), of 1.5 hp capacity, to generate the required pressure gradient. A transparent pliable plastic tube of ample length and diameter was used to hold the specimen membrane by steel clips. The other end of the tube was connected to the compressor. A measuring cylinder of 10ml capacity was used for measuring the flow rate. An adjustable stand was used to hold the setup upright. For sealing the filters, epoxy resin was used. The filter elements were secured using pipe clips. Branches from cypress (*Cupressus cashmeriana*) were cut with a manual hack saw. The branches were cut into small pieces of desired size by an electric saw. 1.5 cm thick sections with a cross section of approximately 2.5 cm^2 were cut from the branch. The sections were inspected for the presence of any nodes. The bark was peeled off and the sections were soaked in distilled water. The ends were cleaned with ethanol using a brush. Then the sections were inserted into the end of the plastic tube and sealed using epoxy resin. The ends were secured using pipe clips.

Filtration and flow rate measurement

The compressor tank was prefilled until a specific pressure was reached. The pressure used for the study was 0.295 bar (gauge pressure) equivalent to 3 m head of water, for our filtration experiments. The contaminated water was introduced into the tube which was subjected to high pressure from one end, the other end was sealed with the wood membrane. Then the same end was connected to the compressor tank and the pressure was applied. The filtrate was collected in a measuring cylinder and the flow rate was measured using stopwatch. Three readings were taken and the flow rate was averaged. The samples were pre-treated with alum before the filtration process. The filtrate samples were collected and sealed in the test tubes to avoid any contamination from the atmosphere (Fig. 3). In order to determine the particle size of the contaminants before and after the filtration Anton Paar LiteSizer 500 was used.

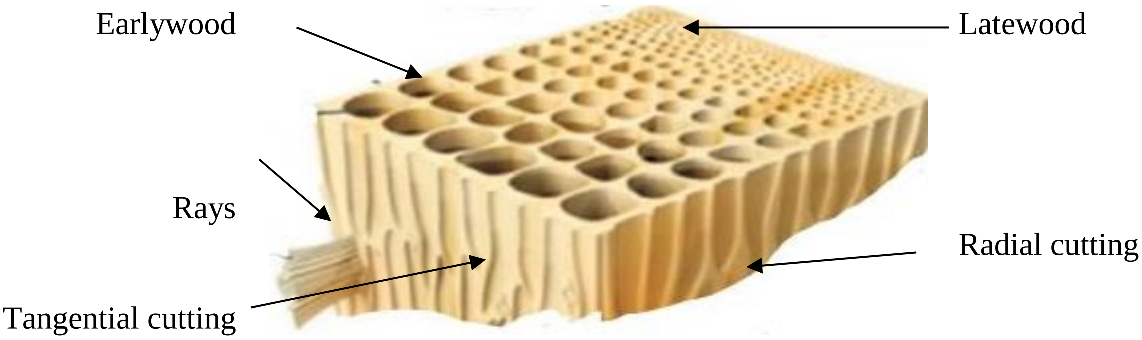

Fig. 1. (a) Anatomy of wood depicting its porosity [1]

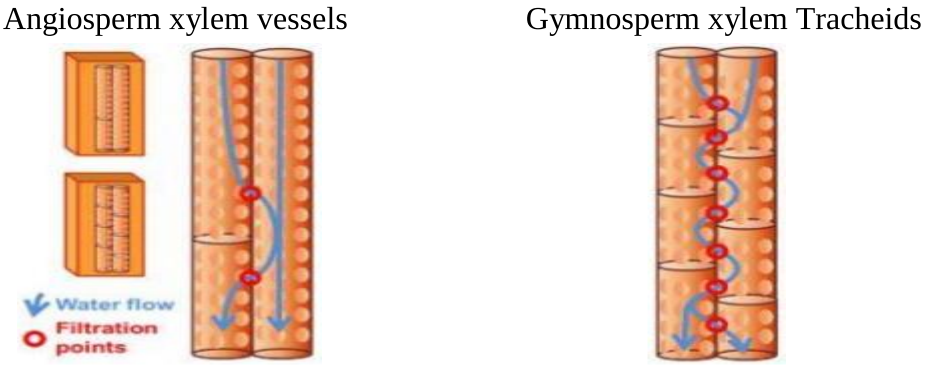

Fig. 1. (b) Flow through xylem conductive tissue [2]

RESULTS AND DISCUSSION

In the preliminary testing phase, the efficacy of the filter was tested visually by filtering a suspension of clay and sand in water. It was compared with the unfiltered water sample. The filtrate was clear, indicating that the filter was capable of removing turbidity caused by suspended and colloidal impurities. The flow rate measurements revealed that the filter with a thickness of about 0.65 cm and cross-sectional area of 100 cm^2 had a flow rate of 4 liters per day under a gauge pressure of 0.295 bar (3 m of water) which is enough to meet the daily drinking water needs of one person. The flow rate was directly proportional to the applied pressure and the filter cross-sectional area and inversely proportional to the membrane thickness. The hydrodynamic conductivity was calculated using Eq. (1):

$$Q = kA\Delta P/l \qquad (1)$$

where Q is the volumetric flow rate (m^{3}s^{-1}), ΔP is the pressure difference across the filter (Pa), A and l are the cross-sectional area (m^2) and the thickness of the filter (m), respectively. The value of hydrodynamic conductivity was in the range of 8 to 10 $\times 10^{-13}$ m^{2}Pa^{-1}s^{-1}.

Particle size analysis (Fig. 4) was performed on the collected samples to determine the effectiveness of the membrane to eliminate the suspended matter. The tests revealed that the size of the contaminants ranged from ~90 nm to ~10 µm. Then the filtrate was analyzed. The size of the contaminants in the filtrate ranged from ~90 nm to ~300 nm. The filtrate particle size distribution peaked at ~100 nm. The filter was effectively able to reject particles larger than ~300 nm. The rejection rate was greater than 99.8%. Most pathogenic bacteria larger than this size are therefore removed. For example, *Vibrio cholera*, the bacteria that causes the water-borne disease cholera is 1-3 µm in length and 0.5-0.8 µm in diameter and the typhoid-causing bacterium *Salmonella typhi*, is 2 – 5 µm in length and 0.5 - 1.5 µm in diameter. This implies that the filter is capable of filtering out most fungal spores and bacteria from polluted water. Fourier Transform Infrared Spectroscopy (FTIR) test was done using Perkin Elmer Spectrum IR on the unfiltered and filtered samples. FTIR plots the transmittance, which is percentage amount of radiation absorbed by the sample *versus* wave number (cm^{-1}), which is defined as the reciprocal of wave length. The results were identical for the unfiltered and filtered samples. It was concluded that no change in the chemical composition took place. According to preliminary tests, the filter successfully eliminated the turbidity.

The size of the pores in the pit membranes ranges in nanometers, and hence, it is effective in removing suspended and colloidal impurities. Flow rate experiments indicated that flow rate is directly proportional to cross section area and pressure difference and inversely proportional to filter thickness.

A thicker filter offers more resistance to the flow of water through it. However, a thicker filter increases the rejection rate up to a certain limit (Fig. 5). In a separate experiment the filtered samples were pre-treated with alum. It was observed that the treatment with alum prior to filtration increased the flow rate and the filter life for turbid water. No change in chemical composition was detected using FTIR analysis. The profiles in Fig. 6 and Fig. 7 were similar, implying that the unfiltered and filtered samples had the same broad chemical composition. This was to be expected as the given study lacks chemical treatment procedures. Chemical contaminants can be adsorbed using adsorbents such as activated carbon. The experimental results of the study are presented in Table 1 for a cross sectional area of 100 cm^2 and P=0.295 bar. After conducting experiments on fresh wood, an additional investigation was performed on the dried wood. It was found that dried wood is not effective for filtration. The idea was thus discarded as the flow rate was by two orders of magnitude slower. Also to compensate for the decrease in flow rate, thinner sections were cut, but no appreciable filtration effect was observed in this case. The thinner sections were also prone to cracking on application of pressure.

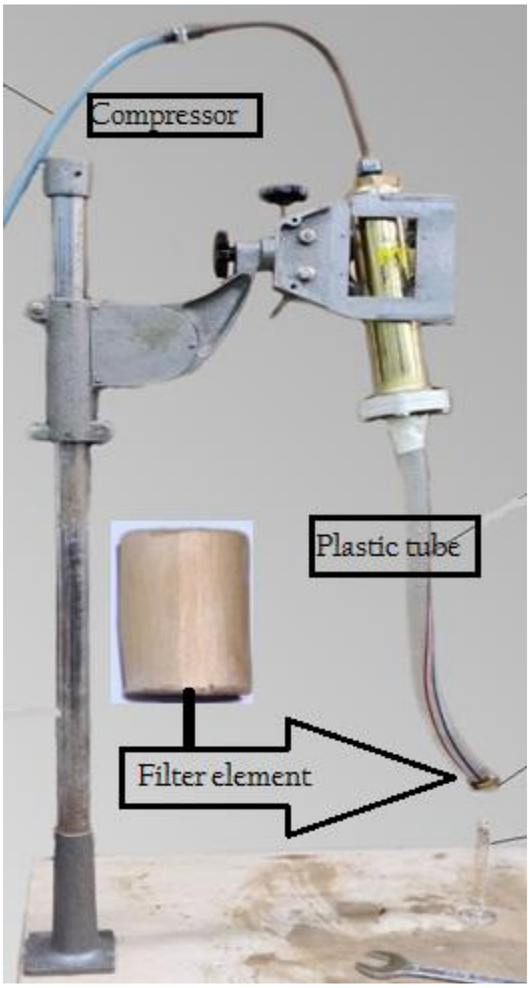

Fig. 2. Set-up used for experiments

Fig. 3. Test results

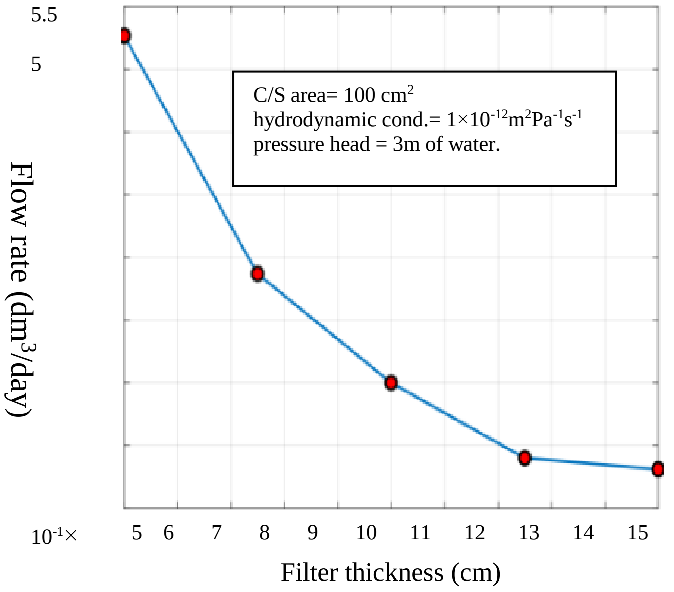

Fig. 4. Particle size distribution in the sample before filtration and after filtration

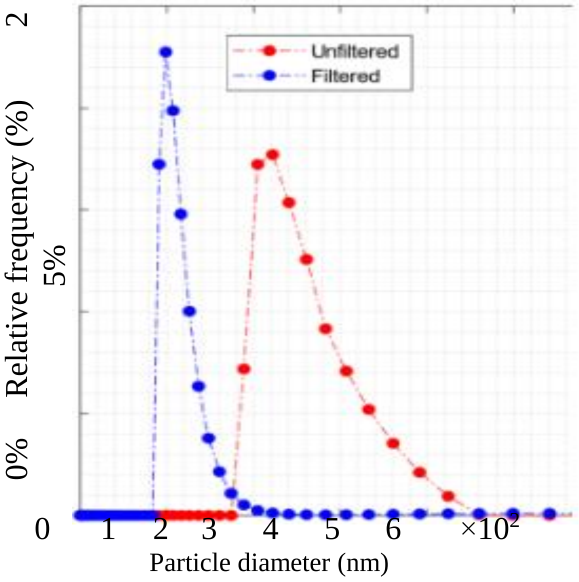

Fig. 5. Variation of the flow rate with filter thickness

Table 1. Experimental results

Thickness of filter element (cm)	Time taken	Flow rate (ml/s)	Flow per day (dm^3/day)
0.50	164	0.061	5.27
0.75	257	0.039	3.37
1.00	345	0.029	2.50
1.25	454	0.022	1.90
1.50	476	0.021	1.81

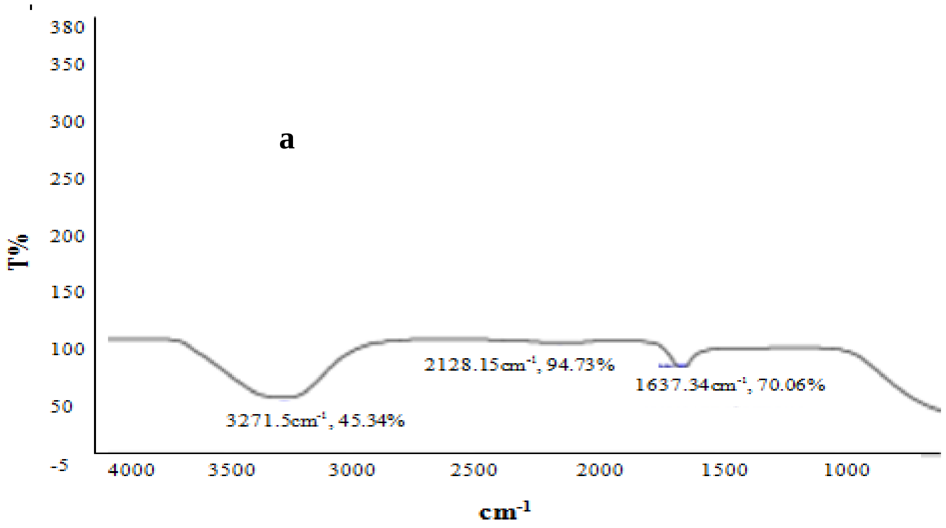

Fig. 6. FTIR spectrograph of unfiltered sample

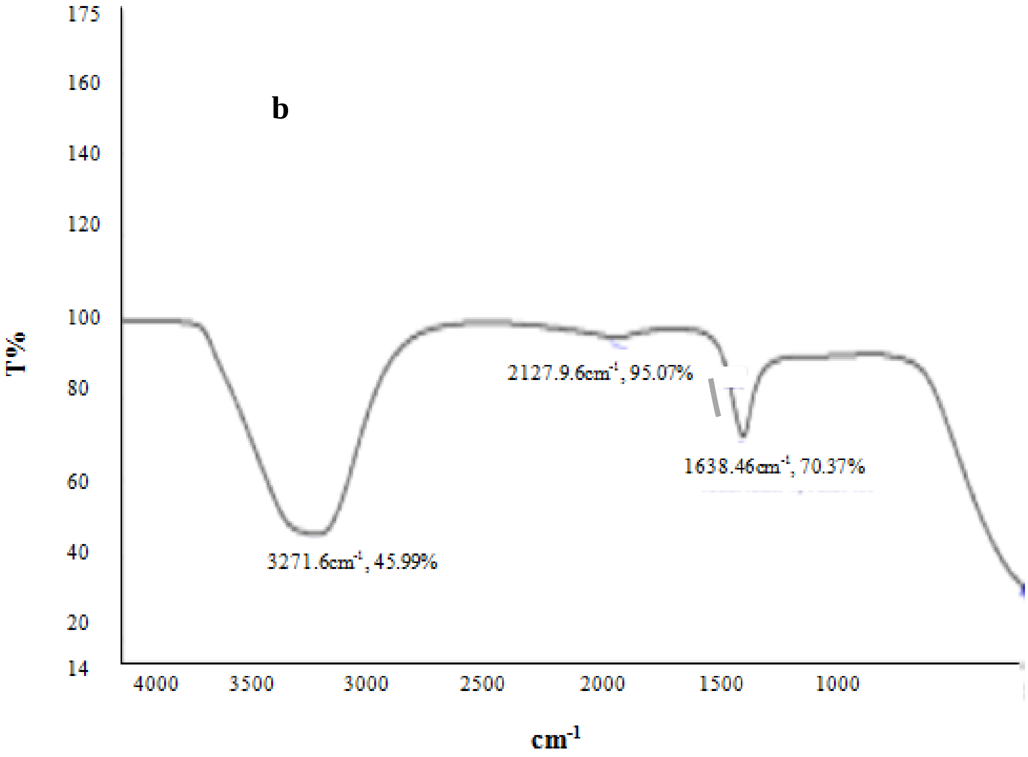

Fig. 7. FTIR spectrograph of filtered sample

CONCLUSIONS

Plant xylem can be used effectively for filtration of water. A gymnosperm xylem filter was prepared using *Cupressus cashmeriana*, which was able to effectively filter out particles larger than 300 nm. The particle rejection rate was 99.8%. A flow rate of 4 liters per day was obtained through a filter element of cross-sectional area 100 cm^2 under a gauge pressure of 0.295 bar. The chemical composition was found to remain unchanged after filtration.

Cheap conventional treatment methods like treatment with alum before filtration can increase the filter life significantly. There is a bright scope for investigating other gymnosperm species which have much smaller pit membranes for filtration of viruses and other pathogens. Wood seasoning and its effect on filtration need further study. Ion exchange methods can be used in conjunction with the xylem filter to develop a much more effective filtration system.

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